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Study of polonium isotopes ground state properties by simultaneous atomic- and nuclear-spectroscopy

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Abstract

We propose to systematically study the ground state properties of neutron deficient $^{192-200}\text{Po}$ isotopes by means of in-source laser spectroscopy using the ISOLDE laser ion source coupled with nuclear spectroscopy at the detection setup as successfully done before by this collaboration with neutron deficient lead isotopes. The study of the change in mean square charge radii along the polonium isotope chain will give an insight into shape coexistence above the mid shell $N = 104$ above the closed shell $Z = 82$. The hyperfine structure of the odd isotopes will also allow determination of the nuclear spin and the magnetic moment of the ground state and of any identifiable isomer state. For this study, a standard UC_x target with the ISOLDE RILIS is required for 38 **shifts**.



Introduction

With the Resonance Ionisation Laser Ion Source (RILIS) at ISOLDE, isobaric beam contamination is greatly suppressed and, thanks to a recent on-line test of new ionisation schemes, beams of neutron-deficient polonium ($Z = 84$) isotopes far from stability are within reach. Moreover, due to inherently large optical isotope shift of several GHz per amu in the $Z = 82$ region and a magnetic hyperfine splitting of the order of 10 GHz, it is feasible to use the RILIS for direct atomic spectroscopy. Indeed, both the first and second steps of the ionisation process are sensitive to the nuclear ground state properties. Hence the change in the mean square charge radius and, for non-zero nuclear spin, the magnetic moment can be determined, allowing systematic trends in the nuclear structure along chain of isotopes to be uncovered.

It is of particular interest in this region to extend the knowledge on the charge radii and nuclear moments approaching the mid-shell $N = 104$ to directly test the predictions of nuclear models such as the Finite Range Droplet Model [1, 2], the Beyond Mean Field [3] and Relativistic Mean Field approaches [4] or the Interacting Boson Model [5].

Physics interest

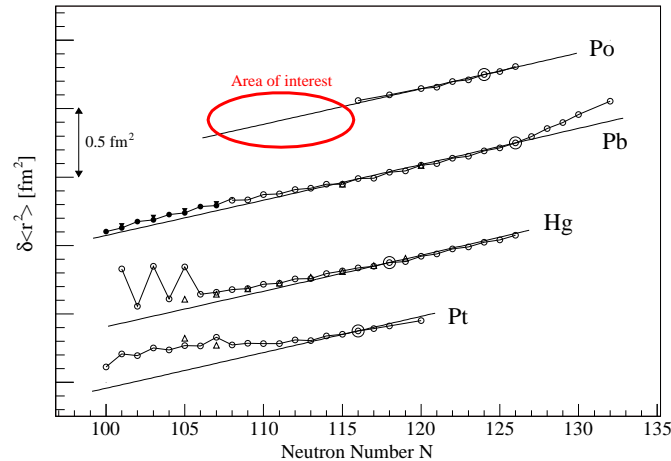


Figure 1: Change in mean square charge radius as a function of the neutron number N for Pt [6], Hg [7], Pb [8, 9, 10, 11, 12] and Po [13]. The points represent the experimental data while the line is the spherical droplet model predictions.

Shape coexistence at low excitation energy in nuclei is a phenomenon for which interest has been continuously growing on both the experimental and theoretical fronts [14, 15, 16, 17]. The region around the neutron mid-shell $N = 104$ and closed proton shell $Z = 82$ is especially prolific. The platinum isotope ($Z = 78$) ground states show a transition from the weakly deformed oblate shape at $A < 176$ and $A > 188$ to a strongly prolate configuration for $176 \leq A \leq 188$ with shape coexistence in the mass region of the transition between the two groups of deformation [6, 18, 19]. Similarly the mercury isotopes ($Z = 80$) around $N = 104$ show shape coexistence and shape transition and, for

the lightest isotopes ($N \leq 106$), a large odd-even staggering in the charge radii as well as a large shift between the ground state and the isomer charge radii [7].

More recently, the mean square charge radii of the neutron-deficient $^{182-190}\text{Pb}$ isotopes have been studied at ISOLDE under experiment IS407 using the same technique proposed here and by the same collaboration. The study across the mid-shell $N = 104$ along the $Z = 82$ closed shell revealed that lead nuclei charge distributions have only little deviation from the spherical droplet model prediction. This corresponds to a weak mixing only despite the proximity of a 0^+ excited states for the lightest nuclei. A comparison with Beyond Mean Field calculation [3] and IBM-type prediction [20] shows that this deviation is explained by the sensitivity of the mean square charge radius to small changes in the pairing gap and/or the weak mixing in its wavefunction [11]. The success of this experiment was two-fold. First the technique was proved to be successful down to the very short-lived ^{182}Pb isotope ($T_{1/2}=55$ ms) with a count rate as low as a few ions per second. Secondly, the results obtained challenged the models beyond what was originally expected and triggered discussion toward a better understanding of the Beyond Mean-Field model and the Interacting Boson Model. [11]

The polonium isotopes ($Z = 84$) are important for understanding the transition across the proton shell closure of $Z = 82$. Although some studies have been performed on the neutron-deficient isotopes [21, 22, 23, 24, 25, 26, 27, 28], the study of the charge radii is limited to the longest lived isotopes $^{200-210}\text{Po}$ [13]. The status of the study of charge radii around $Z = 82$ is summarised in Fig. 1.

The recent α -, β - and γ -spectroscopy studies on neutron-deficient polonium isotopes down to $A = 190$ have indeed highlighted ground state shape coexistence. Several nuclear α - and β -decay experiments have concluded that the ground state has a spherical shape near the closed neutron shell $N = 126$ and that the excited oblate deformed states become lower in energy toward the neutron-deficient region [21, 23, 26] and a strong mixture between the two configurations is observed for ^{194}Po [22]. ^{192}Po is the first isotope where the oblate deformed state becomes the main component in the ground state, as observed by in-beam γ -spectroscopy [24]. In ^{191}Po , it was shown from the large hindrance in the α -decay that the $13/2^+$ isomer is deformed and possesses an important intruder component [25]. In ^{190}Po , mother nucleus of ^{186}Pb where triple shape coexistence was first observed [16], a low-lying prolate band has been identified [27]. Finally, a recent study of $^{186-188}\text{Po}$ α -decay suggests that the ground state of those isotopes is in a deformed prolate state [28]. Those observations should be reflected on the charge radii similarly as in the case of mercury and platinum although the crossing of the proton gap makes systematic predictions impossible.

This will also provide an opportunity to study the α -decay of those isotopes. Although the nuclear spectroscopic study of the polonium isotopes has been prolific [21, 22, 23, 24, 26, 27, 28], it remains a unique occasion to study them in an isobarically cleaner beam. The study of isomerically separated beams will also be possible, providing unprecedented opportunities to study the odd isotopes

Experimental Method

In-source laser spectroscopy with RILIS

The RILIS is a powerful tool for ISOLDE that has provided a large number of isobarically clean beams or has enabled the production of several beams that have been otherwise unattainable [29, 30, 31]. Isomer separation with RILIS has been successfully applied to provide beams used for nuclear moments studies, mass measurements and, more recently, for experiments using post-accelerated isomer beams [32, 33, 34, 35]. Additionally, the RILIS itself has proven to be a useful measurement tool, yielding nuclear structure information contributing to the knowledge of nuclear structure [11, 12].

The experimental method will be similar to that previously used at the IRIS on-line mass separator facility in PNPI [36] for resonance ionisation spectroscopy of rare-earth isotopes and, at ISOLDE, for experiment IS407 to study the neutron deficient lead isotopes. Polonium isotopes will be resonantly ionised with the RILIS with the laser for the spectroscopic transition operating in with a narrow band (1GHz) mode. The produced isotopes will be observed through their characteristic decays by nuclear spectroscopy.

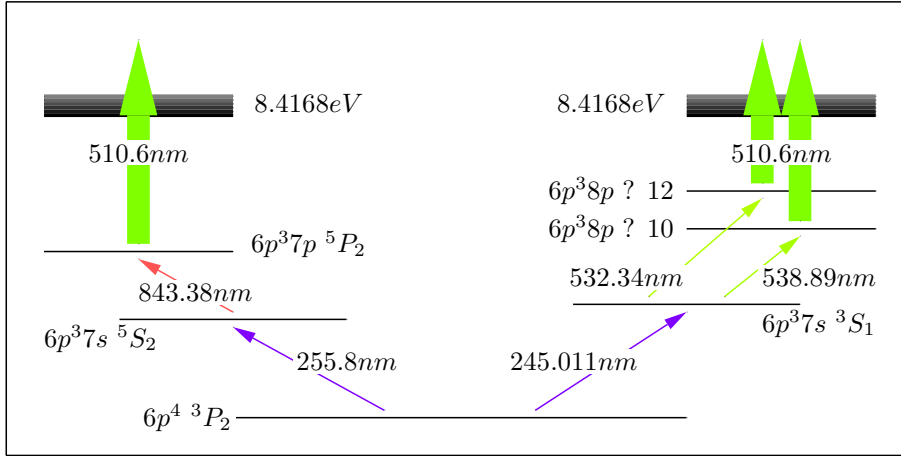


Figure 2: RILIS excitation schemes for ionising polonium.

Two laser ionisation schemes of polonium, shown in Fig. 2, were successfully tested in November 2006 yielding the results shown in Table 1. [37] The saturation of all the five resonant transitions involved was confirmed. The schemes are deemed particularly suitable for the study of mean square charge radii since each resonant transition involves an electron in the 7s orbital. The wavefunctions of the s-electrons have a high degree of overlap with the nucleus, atomic spectroscopy involving these transitions yields the information of greatest interest. To perform atomic spectroscopy, any of the first two resonant transitions can be scanned over a frequency range, giving a level of freedom in performing the measurements whilst minimising the propagation of uncertainties and the linewidth of the studied transition. The centroid frequency and the structure of the transition give the atomic properties of the isotope, yielding then the nuclear information.

As was the case during the earlier experiment by this collaboration on the lead isotopes, the dye laser used for the atomic spectroscopy should have a reduced linewidth and care

should be taken to avoid power broadening. Careful monitoring of all the parameters and regular checks of a reference isotope will ensure an appropriate normalisation procedure.

Nuclear detection system

The α detection system is the same as for IS407. The incoming beam is deposited on a thin carbon foil ($20\mu\text{g}\cdot\text{cm}^{-2}$) on one of 10 possible positions of the Windmill, a rotating wheel that can host two silicon particle detectors for α detection, an entry for a germanium detector for γ detection and a detector for electron conversion. One of the α detectors is placed at the implantation position while the other is placed away from the incoming beam to study only decays of longer lived isotopes. The foils can be regularly moved to bring in a foil with less or even no activity. The background from long lived contaminants can be estimated at the second α detector while the isotopes of interest can be separated from the contaminants by using the different energy of the α particles emitted.

The data acquisition system remains unchanged from the previous experiment. The α spectra will be measured over an integral number of the PSBooster cycles and stored in separate data files for each point of the laser scan.

For the nuclear spectroscopy, a Ge detector will be added to the standard α detection setup to allow for α - γ coincidence as well as a SiLi detector for electron conversion studies.

Production and Yields

Isotope	Yield [μC^{-1}]	Half-life [s]	Isomer	Yield [μC^{-1}]	Half-life [s]
^{190}Po	N/A	0.002			
^{191}Po	N/A	0.0155			
^{192}Po	N/A	0.0332			
^{193}Po	$6.5 \cdot 10^1$	0.42	^{193m}Po	$1 \cdot 10^2$	0.24
^{194}Po	$2.5 \cdot 10^3$	0.392			
^{195}Po	$2 \cdot 10^4$	4.64	^{195m}Po	$5 \cdot 10^4$	1.92
^{196}Po	$4.7 \cdot 10^5$	5.8			
^{197}Po	$2.5 \cdot 10^5$	53.6	^{197m}Po	$2 \cdot 10^6$	25.8
^{198}Po	$7 \cdot 10^6$	106.2			

Table 1: Yields and half-lives of the polonium isotopes of interest with a UC_x target (density $50\text{g}\cdot\text{cm}^{-2}$) [37]. The left column is for the ground states while the right column is for the isomeric states.

Target

The production of neutron-deficient heavy elements around the lead region with UC_x targets has been possible at ISOLDE for a few years already [30]. Such beams have been used in the laser spectroscopy experiment IS407 where lead isotopes were studied down to $A = 182$ and $A = 189$ respectively [11, 12, 38]. Those studies were performed with a standard UC_x target coupled to the RILIS.

We propose to perform the experiment with a standard UC_x target.

Yields

The yields for polonium were measured with the RILIS using the α detection system as explained in the preceding section. The obtained values are shown in Table 1. Those yields compare to the lead yields with a difference of 10 mass units down to $1.2 \cdot 10^1$ ions/ μC for ^{183}Pb compared to $6.5 \cdot 10^1$ ions/ μC for ^{193}Po . [39] Measurements down to ^{182}Pb were achieved [11]. One can thus expect a similar outcome with the polonium study down to ^{192}Po where the mixing is expected to change drastically.

Beam time request

As mentioned while discussing the yields, the situation is very similar to the lead isotope chain study. Therefore a similar number of shifts are asked. To recall from IS407, 38 shifts were asked to perform the atomic and nuclear spectroscopy studies.

Due to the absence of stable isotopes, the RILIS optimisation and reference measurements could be done only with radioactive isotopes. This will definitely take more time with respect to the stable isotope scans in the case of the lead. In addition, the hyperfine structure of the odd polonium isotopes is more complicated than that of lead. We plan to carry the following measurements

2. Calibration isotope shift measurements for the already studied $^{200-210}\text{Po}$,
- 3-4. Isotope shifts between the even isotopes ^{200}Po , ^{198}Po , ^{196}Po , ^{194}Po and ^{192}Po ,
5. Hyperfine structure and isotope shift measurements for the odd isotopes $^{193-205}\text{Po}$,
6. Nuclear spectroscopy of the lightest isotopes with the lasers in broadband mode.

Measurements of the hyperfine structure of the odd polonium isotopes is more complicated than for the lead isotopes and require thus the use of a different transition. This will have to be performed separately. The total number of shifts requested is calculated in Table 2.

1. RILIS setup and optimisation (2 shifts per run)		4 shifts
2. isotope shifts	$^{200-202-204-206-208-210}\text{Po}$	3 shifts
3. isotope shifts	$^{194-196-198-200}\text{Po}$	6 shifts
4. isotope shift	^{192}Po	8 shifts
3. isotope shifts and hyperfine structures	$^{193-195-197-201-203-205}\text{Po}$	14 shifts
4. nuclear spectroscopy		3 shifts
Total number of requested shifts		38 shifts

Table 2: Shift request.

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